EXTRASOLAR REFRACTORY-DOMINATED PLANETESIMALS: AN ASSESSMENT

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ABSTRACT

Previously published observations of 60 externally-polluted white dwarfs show that none of the stars have accreted from intact refractory-dominated parent bodies composed mainly of Al, Ca and O, although planetesimals with such a distinctive composition have been predicted to form. We propose that such remarkable objects are not detected, by themselves, because, unless they are scattered outward from their initial orbit, they are engulfed and destroyed during the star's Asymptotic Giant Branch evolution. As-yet, there is at most only weak evidence supporting a scenario where the composition of any extrasolar minor planet can be explained by blending of an outwardly scattered refractory-dominated planetesimal with an ambient asteroid.

Subject headings: planetary systems – stars, white dwarf

1. INTRODUCTION

How do rocky planets form? Is Earth normal? Are there extrasolar planetesimals with exotic compositions? Although such questions have received an enormous amount of theoretical attention (Armitage 2010), there are relatively few observational constraints. Studies of externally-polluted white dwarfs provide an opportunity to address these topics.

Amassed evidence (Farihi et al. 2009, 2010; Gaensicke et al. 2006, 2007, 2008; Jura 2008; Kilic et al. 2006; Reach et al. 2005; Zuckerman et al. 2010) has provided compelling support for the scenario that the heavy elements in white dwarfs with $T < 20{,}000$ K usually derive from rocky planetesimals. The widely accepted model is that an asteroid's orbit is perturbed so that it passes within the white dwarf's tidal radius where it is destroyed, a circumstellar disk is formed, and eventually this material is accreted onto the host star (Bonsor et al.

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2011; Debes & Sigurdsson 2002; Jura 2003; Rafikov 2011). Consequently, spectroscopic determination of the atmospheric abundances in externally-polluted white dwarfs is a powerful tool to measure the elemental compositions of extrasolar minor planets (Zuckerman et al. 2007). This topic was comprehensively discussed in Jura (2008) and more recently reviewed in Jura (2013).

Recent observational progress in the study of externally-polluted white dwarfs has been substantial. Largely by using the *Spitzer Space Telescope*, 30 white dwarfs with dust disks that lie within the star's tidal radius have been identified (Farihi et al. 2009, 2012a; Brinkworth et al. 2012; Xu & Jura 2012). The first measurement of all major elements in a polluted white dwarf was performed by Klein et al. (2010), and, as reported in more detail below, results for more stars have been announced. Characteristic minimum masses of the accreted parent bodies of the best studied systems require asteroids with diameters greater than 100 km, likely remnant planetesimals from the era of planet formation. These data for externally-polluted white dwarfs therefore uniquely enable detailed assessment of models for the formation and evolution of rocky planets.

In conventional planet formation models, the condensation of gas into solids is controlled by the gas temperature, pressure and composition in the protoplanetary disk midplane. For example, Earth is largely composed of material that condenses at $\sim$1100 K (Allegre et al. 2001); it is presumed that this result reflects the local disk physical conditions at $\sim$1 AU from the Sun at the time when the first planetesimals that grew into Earth were formed (Cassen 1994; Hersant et al. 2001). Similarly, the existence of icy bodies in the outer solar system is explained by their formation beyond a snow line, the region where H_2O condenses into ice and contributes as much as 50% to the mass of a newly-formed planetesimal (Lecar et al. 2006; Garaud & Lin 2007; Oka et al. 2011).

There is now evidence from externally-polluted white dwarfs that these familiar models for thermal segregation in the solar system's protoplanetary disk can be extrapolated to extrasolar planetary systems to explain the measured volatile-element compositions of extrasolar planetesimals. That is, formation interior to a snow line can explain the results of Dufour et al. (2012) that ice comprised less than 1% of the mass of the parent body accreted onto J073842.56+183509.06 and Jura & Xu (2012b) that H_2O was less than 1% of the mass accreted onto an ensemble of nearby externally-polluted white dwarfs. Additionally, carbon within extrasolar planetesimals is often deficient by at least a factor of ten compared to its "cosmic" abundance (Jura 2006; Jura et al. 2012a; Gaensicke et al. 2012; Koester et al. 2012). Therefore interstellar grains containing carbon that entered the inner protoplanetary disks must have been vaporized where gas temperatures likely exceeded 500 K (Lee et al. 2010).

Bond et al. (2010a) have considered standard models for protoplanetary disks and proposed that there is a zone with a temperature near 1400 K where only the most refractory elements condense to form long-lived planetesimals. Local remnants of such a process might be the calcium aluminum inclusions (CAIs) in meteorites that may have been produced in the inner solar system (Ciesla 2010) when the disk was no older than 3×10^5 yr (Young et al. 2005) and perhaps as young as 2×10^4 yr (Thrane et al. 2006). Sunshine et al. (2008a,b) have proposed that some main belt asteroids with high fractions of refractory elements may be composed of blends of exceptionally refractory planetesimals that were formed in the inner solar system and scattered outwards to collide and partially merge with an ambient object. Although the magnitude of such refractory-rich contamination is uncertain (Hezel & Russell 2008), perhaps similar radial mixing measurably occurred in extrasolar planetary systems.

There are at least two ways by which we might infer the long-lived existence of refractory-dominated planetesimals. First, most obviously, such an object might be accreted intact by a white dwarf and the heavy elements in the atmosphere of the star would be largely Al, Ca and O. Second, more subtly, accreted material might be a blend of a more "normal" Earth-like composition with a refractory-dominated planetesimal that was scattered outwards from its original orbit (Carter-Bond et al. 2012). This blending may occur either by the collision of two asteroids and a subsequent partial or complete merging, or simply by two different asteroids being independently tidally-disrupted, but from our perspective, being simultaneously accreted by an externally-polluted white dwarf.

In Section 2, we summarize relevant observations of externally-polluted white dwarfs. In Section 3, we describe a toy model to explain why intact refractory-dominated planetesimals have not yet been found. In Section 4, we consider the possibility that refractory-rich material in some observed polluted white dwarfs results from blending of refractory-dominated planetesimals into the observed contaminating material. In Section 5 we put our results in perspective and in Section 6 we present our conclusions.

2. CURRENT OBSERVATIONS

Ca II 3933 Å is the strongest heavy-element line in the optical spectrum of polluted white dwarfs cooler than 15,000 K (Sion et al. 1990) while Mg II 4481 Å and/or Mg I between 3832 Å and 3838 Å often also are detected. Because refractory-dominated planetesimals are predicted to be largely composed of O, Ca and Al, we use observed value of $n(\mathrm{Mg})/n(\mathrm{Ca})$ to determine if the white dwarf has accreted such a parent body. Previously published results

for 60 polluted white dwarfs[1] with expected relative errors less than 0.5 dex are displayed in Figure 1 where $n(\mathrm{Mg})/n(\mathrm{Ca})$ is plotted compared to the white dwarf's effective temperature, a measure of the star's cooling age. We also display $n(\mathrm{Mg})/n(\mathrm{Ca})$ for a representative type A CAI, a value that is midway between the higher ratio measured for type B CAIs (Grossman 1980) and the lower ratio predicted for refractory-dominated planetesimals (Bond et al. 2010a). We see that Mg is always more abundant than Ca, as in bulk Earth but not in CAIs. There is no evidence for intact extrasolar refractory-dominated planetesimals.

The average values of log $n(\mathrm{Mg})/n(\mathrm{Ca})$ and log $n(\mathrm{Fe})/n(\mathrm{Ca})$ for the ensembles of stars plotted in Figures 1 and 2 are 1.26 and 1.00, respectively. The corresponding solar system values of these two ratios are 1.21 and 1.13, respectively (Lodders 2003). At least on average, the relative abundances of Fe, Mg and Ca among extrasolar planetesimals are approximately solar system-like.

Because different elements gravitationally settle with different rates, the ratio of Mg to Ca in the star's photosphere need not measure the element ratio in the accreted parent body (Dupuis et al. 1993; Koester 2009). The display in Figure 1 is for the "instantaneous" approximation where the observed abundance ratio directly measures the abundance ratio in the parent body. If, instead, the system is in a steady state where the rate of accretion onto the top of the photosphere is balanced by the loss rate at the bottom of the mixing zone, then the observed value of $n(\mathrm{Mg})/n(\mathrm{Ca})$ must be altered by the ratio of the gravitational settling times to infer the true ratio in the accreted asteroid. Typically, this correction is between 0.1 dex and 0.2 dex (Koester 2009; Koester et al. 2011) and therefore does not affect our qualitative conclusion. If the system is in a decaying phase where there accretion is negligible and there is only gravitational settling, then the observed value of $n(\mathrm{Mg})/n(\mathrm{Ca})$ can become much larger than the value in the parent body because Mg typically settles more slowly than Ca (Koester 2009). However, in this decaying phase we would also expect $n(\mathrm{Fe})/n(\mathrm{Ca})$ to become quite small because Fe settles more rapidly than Ca. Of the 60 stars for which data are shown in Figure 1, 50 also have measured values of the Fe abundance. In Figure 2, we display $n(\mathrm{Fe})/n(\mathrm{Ca})$. Again, there is no evidence for refractory-dominated planetesimals.

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[1] Included are 26 stars from Koester et al. (2011), 8 stars from Kawka et al. (2011) and 5 stars from Zuckerman et al. (2003). Also included are GD 40 and G241-6 (Jura et al. 2012a), GD 362 (Zuckerman et al. 2007), G149-28 and NLTT 43806 (Zuckerman et al. 2011), PG 1225-079 and HS 2253+8023 (Klein et al. 2011), NLTT 1675 and NLTT 6390 (Kawka & Vennes 2012), WD 0738-172 (Koester & Wolff 2000), van Manaan 2 (Wolff et al. 2002), PG 1015+161 and WD 1226+110 (Gaensicke et al. 2012), GALEX 193156.8+011745 (Melis et al. 2011; Vennes et al. 2011), J073842.56+183509.06 (Dufour et al. 2012), HE 1349-2305 (Melis et al. 2012), Ton 345 (Gaensicke et al. 2008), SDSS J095904.69-020047.6 (Farihi et al. 2012a), GD 61 (Farihi et al. 2011a), G77-50 (Farihi et al. 2011b), and GD 16 (Koester et al. 2005).

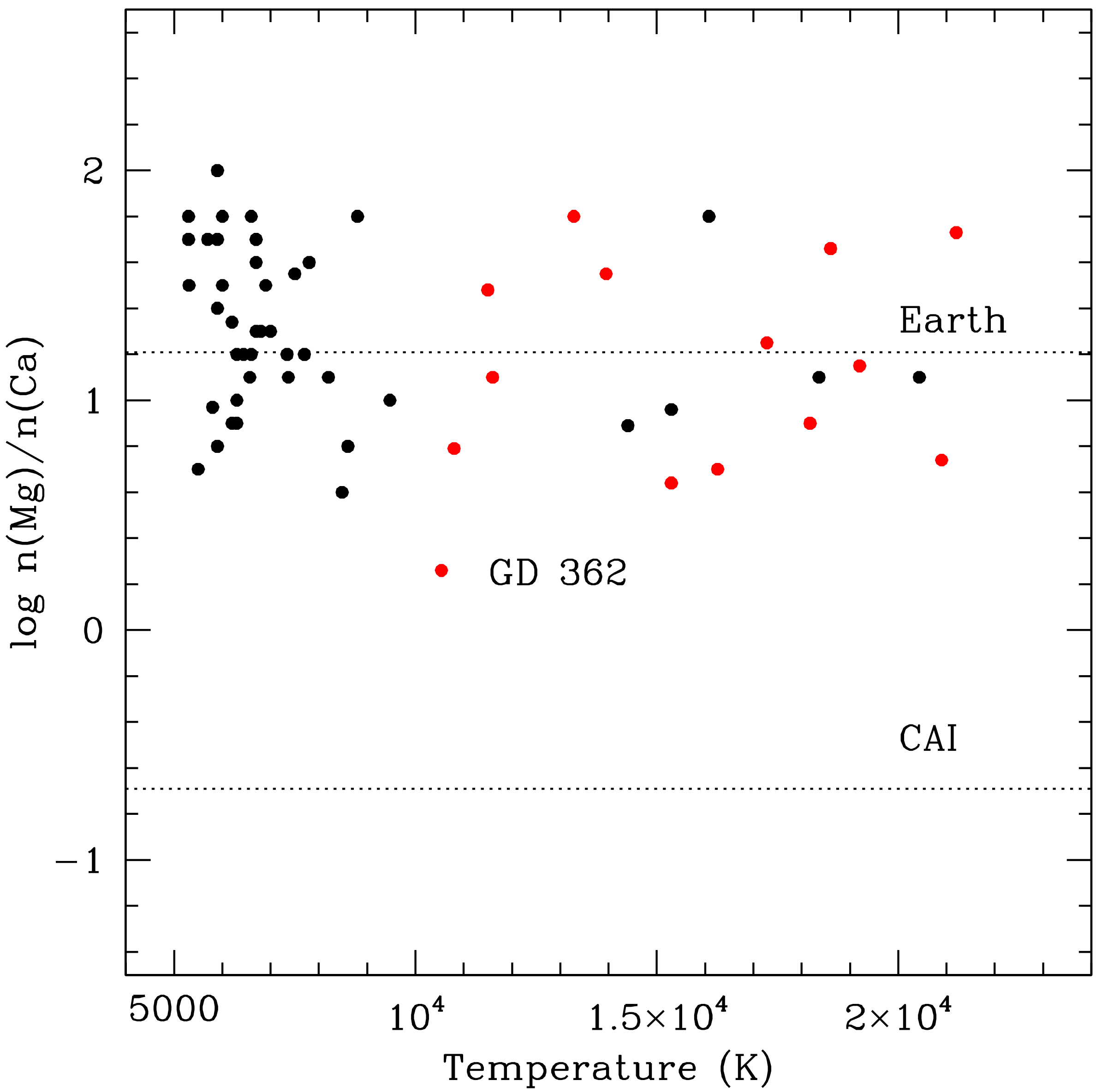

Fig. 1.— Plot of published values of log n(Mg)/n(Ca) for 60 externally-polluted white dwarfs vs. stellar effective temperature. Although each study is different, the typical errors bars, when reported, are 0.2-0.3 dex, and for clarity, they are suppressed here. The horizontal dashed lines are for bulk Earth (Allegre et al. 2001) and a representative type A CAI (Grossman 1980). There is no system where n(Mg)/n(Ca) is close to the ratio found in CAIs. Red and black points denotes white dwarfs with and without dust disks, respectively (Farihi et al. 2009; Xu & Jura 2012). There is no evidence that the accretion from stars with dust is compositionally different from stars without dust.

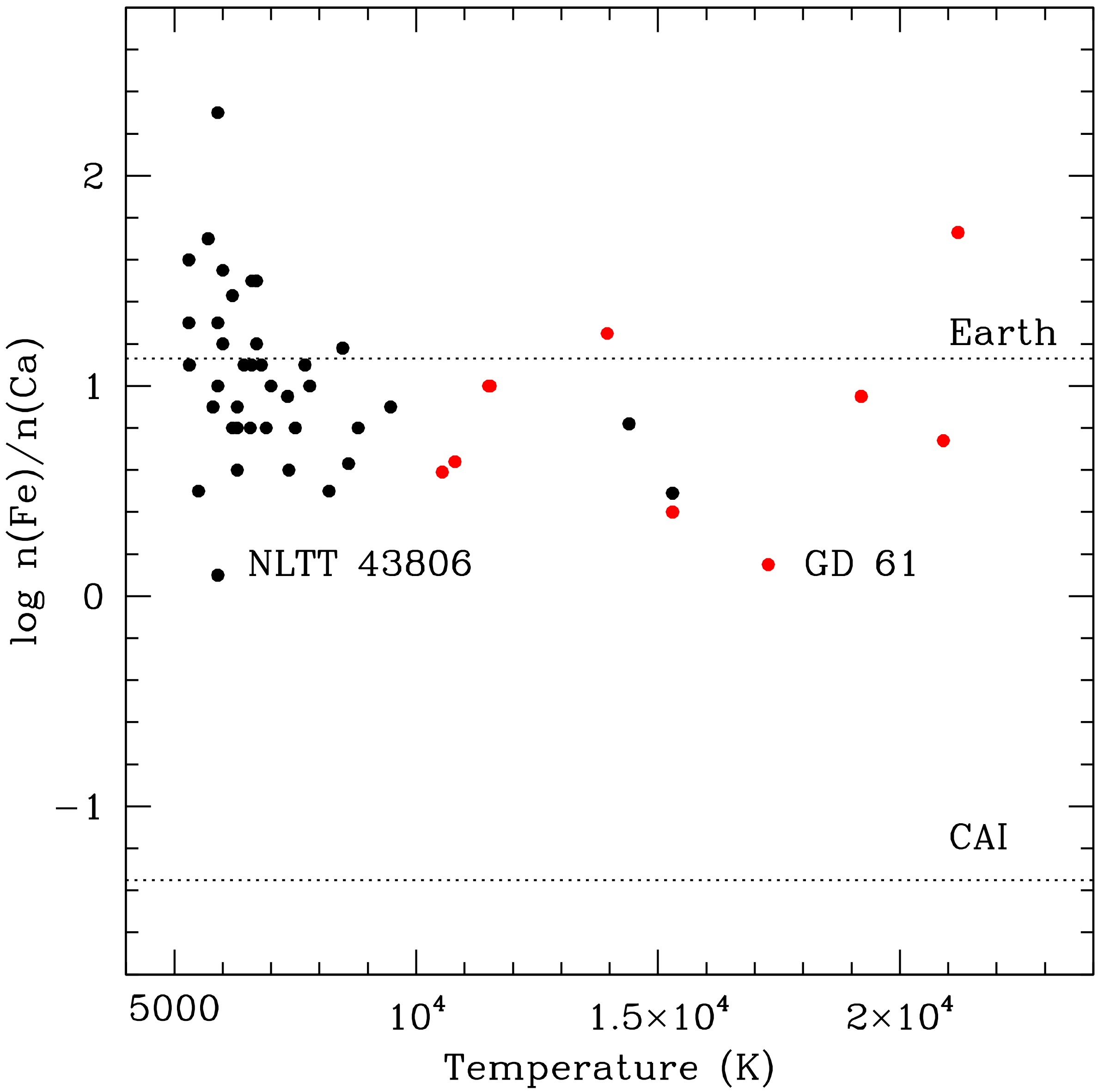

Fig. 2.— Same as Figure 1 except for log n(Fe)/n(Ca) for the 50 stars where Fe is reported. There is no system where n(Fe)/n(Ca) is close to the ratio found in CAIs.

3. DETECTABILITY OF NON-SCATTERED REFRACTORY-DOMINATED PLANETESIMALS

We now consider a very simplified model to assess the circumstances where we might be able to detect intact refractory-dominated planetesimals accreting onto white dwarfs. We first estimate the orbital radius where such planetesimals may form in a protoplanetary disk. We then determine if the surviving planetesimals are engulfed during the evolutionary phase when the star is on the Asymptotic Giant Branch (AGB). If not subsumed, we assume planetesimal survival into the phase when the star is a white dwarf. In this section, we consider the case where the asteroid remains in the orbital location where it formed; in Section 4, we consider the possibility that some minor planets may be scattered outwards.

3.1. Formation Location

To estimate the orbital location for the formation of refractory-domianted planetesimals, we extend the models of Bond et al. (2010a,b) to higher stellar masses; they mainly considered planet formation around stars of about 1 $M_{\odot}$. Therefore, we assume that refractory-dominated planetesimals form where the midplane disk temperature, T_{mid}, is low enough that calcium and aluminum both form solid oxides, yet high enough that silicon, magnesium and iron remain in the gas phase. For the gas pressures of interest and for a solar system-like composition, this requires that 1340 K $\leq T_{mid} \leq$ 1520 K for 50% condensation (Lodders 2003). For simplicity, we focus on a single condensation temperature of 1400 K.

For a pre-main-sequence star of mass, M_*, which possesses a protoplanetary disk where material is accreting onto the host star with rate, $\dot{M}_*$, the effective temperature at the surface of an opaque disk, T_e, at orbital distance, R, is controlled by dissipation of accretion energy. For $R >> R_*$, where R_* is the stellar radius, then (Hartmann 2009):

$$T_e \approx \left(\frac{3\, G\, M_*\, \dot{M}_*}{8\, \pi\, R^3\, \sigma_{SB}} \right)^{1/4} \tag{1}$$

Here, G and σ_{SB} denote the gravitational constant and Stefan-Boltzmann constant, respectively. The midplane temperature is controlled by the vertical diffusion of radiation and is generally higher than the effective temperature at the disk surface. If the disk has a total gas surface density of Σ_H, and if χ denotes the Rosseland mean opacity, then we define the vertical optical depth from the midplane through the dust layer as:

$$\tau \;=\; \frac{\chi\, \Sigma_H}{2} \tag{2}$$

Because energy flows in both directions and there is no net flux at the midplane, the computed temperature as a function of optical depth is somewhat different from the thermal profile in a stellar atmosphere (Hubeny 1990; Oka et al. 2011), and:

$$T_{mid} \approx \left(\frac{3\,\tau}{8}\right)^{1/4} T_e \tag{3}$$

We now estimate the disk surface density. Bond et al. (2010b) presume a minimum mass solar nebula where Σ_H varies as $R^{-1.5}$. However, because we wish to extrapolate from the solar system to other environments, we adopt a simplified conventional steady state α-disk configuration where viscosity at the midplane controls the energy dissipation and the inward transport of mass[2]. In this case, then (Oka et al. 2011):

$$\Sigma_H \;=\; \frac{\dot{M}_*\,\mu}{3\,\pi\,\alpha\,k_B\,T_{mid}}\left(\frac{G\,M_*}{R^3}\right)^{1/2} \tag{4}$$

where α is the usual dimensionless viscosity scaling factor[3] and μ is the mean molecular weight of the gas. For our fiducial model, we adopt $\alpha = 0.01$, but the uncertainty is substantial (King et al. 2007).

If the material condenses at orbital radius, R_{cond}, where the midplane temperature is T_{cond}, then from Equations (1) - (4), we find:

$$R_{cond} \;=\; \left(\frac{3\,\chi\,\mu}{128\,\pi^2\,\alpha\,k_B\,\sigma_{SB}\,T_{cond}^5}\right)^{2/9}(G\,M_*)^{1/3}\,\dot{M}_*^{4/9} \tag{5}$$

To determine R_{cond}, we now estimate the opacity which depends upon the grain size distribution, maximum particle size and composition. Because we consider the regime where refractory-dominated planetesimals form, we assume that grains are only composed of minerals that are combinations of CaO and Al_2O_3. If we assume that all of the available calcium and aluminum condense, then with abundances from Lodders (2003) which are representative of G-type stars in the solar neighborhood (Reddy et al. 2003), the mass fraction compared to hydrogen that can be condensed into solids, f_{cond}, is 2.5×10^{-4} (Ciesla 2010).

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[2]Much more sophisticated models have been presented (Zhu et al. 2010); including, for example, the possibility of a “dead zone”.

[3]α can be defined either in terms of the isentropic sound velocity or the isothermal sound velocity, a difference of a factor of $\gamma^{1/2}$ where γ is the ratio of specific heats. Following Armitage (2010) in recognizing that uncertainties in the viscosity dwarf this issue, we simply define α in terms of the isothermal sound velocity.

Although the grain size distribution is unknown, we are considering an environment where particles are growing into planetesimals. Therefore, we expect particles to be larger than interstellar grains. It is possible that the grain size distribution follows a power law of the form (D'Alessio et al. 2001):

$$n(a)\,da \propto a^{-2.5}\,da \tag{6}$$

If so, then most of the particles are large enough that the Rosseland mean opacity is determined by the particles' geometric cross sections. If the maximum particle size is a_{max}, then:

$$\chi \;=\; f_{cond}\left(\int_0^{a_{max}} \pi\, a^2\, n(a)\, da\right)\left(\int_0^{a_{max}} \frac{4\pi a^3\,\rho_s}{3}\, n(a)\, da\right)^{-1} \;=\; \frac{9\, f_{cond}}{4\,\rho_s\, a_{max}} \tag{7}$$

Although different minerals have different densities; for our fiducial model, we adopt $\rho_s \approx 3$ g cm^{-3}. If $a_{\rm max} = 1$ mm (D'Alessio et al. 2001), then $\chi = 2.0 \times 10^{-3}$ cm^2 g^{-1}. However, this opacity is uncertain by at least a factor of 10.

We now evaluate Equation (5) for our fiducial model describing the formation of refractory-dominated planetesimals. If $M_* = 1.0$ M$_\odot$, $\dot{M}_* = 3 \times 10^{-6}$ M$_\odot$ yr^{-1}, $T_{cond} = 1400$ K and the gas is composed of molecular hydrogen and helium with a solar fractional abundance so that $\mu = 2.4\ m_H$ where m_H is the mass of a hydrogen atom, we expect $R_{cond} = 0.38$ AU. Therefore, for this stellar mass and accretion rate, we reproduce the results computed in much more detailed models (Bond et al. 2010a).

The temperature in the disk midplane being as high as $\sim$1400 K is mainly a consequence of the accretion rate being greater than 10^{-6} M$_\odot$ yr^{-1} (Hersant et al. 2001; D'Alessio et al. 2005). This presumed rate of accretion is much greater than values assigned to T Tau disks of $\sim 10^{-8}$ M$_\odot$ yr^{-1} (Hartmann 2009). However, because 10% of accretion during a star's pre-main-sequence evolution is accreted during a high luminosity short-lived FU Ori phase (Hartmann 2009), planetesimal formation during this evolutionary phase may occur. In any case, because Earth's composition is well explained by condensation into solids at $\sim$1100 K (Allegre et al. 2001), a short-lived phase solid-forming when the midplane temperature was near 1400 K at 0.4 AU seems plausible.

Equipped with this simple model, we now extrapolate to more massive stars to estimate the orbital location where very refractory planetesimals may form. Although there is wide variability (Hartmann 2009), we assume that the relevant accretion rate for the era of the formation of very refractory planetesimals equals our fiducial value of 3×10^{-6} M$_\odot$ yr^{-1} independent of M_*. Consequently, from Equation (5), we expect that the orbital location of the formation of refractory-dominated planetesimals is:

$$\frac{R_{cond}}{R_\odot} \;=\; 81\left(\frac{M_*}{M_\odot}\right)^{1/3}\left(\frac{\chi}{\chi_0}\right)^{2/9}\left(\frac{0.01}{\alpha}\right)^{2/9} \tag{8}$$

Here, χ_0 is the fiducial opacity.

3.2. Survivability

Even if very refractory planetesimals formed, they might be engulfed and not survive the star's red giant evolution. We now compare the orbital radius of extremely refractory planetesimals with the size of the star when it is on the Asymptotic Giant Branch (AGB).

Denote M_i and M_f as the initial main-sequence mass and the final white dwarf mass. The maximum luminosity on the AGB, L_{AGB}, is approximately (Iben & Renzini 1983):

$$\frac{L_{AGB}}{L_{\odot}} \approx 5.9 \times 10^4 \left(\frac{M_f}{M_{\odot}} - 0.495\right) \tag{9}$$

The initial mass to final mass relationship is (Williams et al. 2009):

$$\frac{M_f}{M_{\odot}} = 0.339 + 0.129 \frac{M_i}{M_{\odot}} \tag{10}$$

For main-sequence stars appreciably more massive than the Sun, then from Equations (9) and (10):

$$\frac{L_{AGB}}{L_{\odot}} \approx 7600 \frac{M_i}{M_{\odot}} \tag{11}$$

We therefore write for the maximum radius of the star while on the AGB that:

$$\frac{R_{AGB}}{R_{\odot}} = 87 \left(\frac{M_i}{M_{\odot}}\right)^{1/2} \left(\frac{T_{\odot}}{T_{AGB}}\right)^2 \tag{12}$$

where T_{AGB} is the star's effective temperature while on the AGB.

With the usual assumption that the planet's orbital radius expands with constant angular momentum as the star loses mass (Veras et al. 2011), then the final distance from the star, R_f is:

$$\frac{R_f}{R_{cond}} = \frac{M_i}{M_f} \tag{13}$$

From Equations (8), (12) and (13) equating M_i with M_*, we write that

$$\frac{R_f}{R_{AGB}} \approx 0.93 \left(\frac{M_{\odot}}{M_i}\right)^{-1/6} \left(\frac{T_{AGB}}{T_{\odot}}\right)^2 \left(\frac{\chi}{\chi_0}\right)^{2/9} \left(\frac{0.01}{\alpha}\right)^{2/9} \left(0.339 \frac{M_{\odot}}{M_i} + 0.129\right)^{-1} \tag{14}$$

The requirement that a planetesimal survive into the star's white dwarf evolutionary phase is that $R_f > R_{AGB}$.

3.3. Results

We show in Figure 3 a plot of R_f/R_{AGB} as a function of a star's initial main-sequence mass. In all cases, we take T_{AGB} = 3000 K (Bertelli et al. 2009). For the fiducial values of the viscosity and opacity, we find that $R_f/R_{AGB} < 1$ for all main-sequence stars of mass less than 6.0 $M_\odot$ corresponding to a white dwarf mass of 1.1 $M_\odot$. Therefore we expect that even if refractory-dominated planetesimals are formed, unless they are scattered outwards, they are destroyed when the star is on the AGB. However, because the parameters with a protoplanetary disk are uncertain, we also show results in Figure 3 for a case with higher opacity and/or lower viscosity. If the opacity is increased by a factor of 10 or α is decreased by a factor of 10 – equivalent changes in Equation (14) – then refractory-dominated planetesimals might survive through the AGB evolution of main-sequence for most stars of interest. Both Ciesla (2010) and Garaud & Lin (2007) employ α = 0.001, a factor of 10 below our fiducial value; it is possible that this lower value of α is appropriate for some protoplanetary disks. The results in Figures 1 and 2 provide support for the fiducial model.

4. DETECTABILITY OF SCATTERED REFRACTORY-DOMINATED PLANETESIMALS

Carter-Bond et al. (2012) computed that refractory-dominated planetesimals may be dispersed throughout a planetary system by the migration of giant planets. If so, then the refractory-dominated planetesimals should survive the star's AGB evolution, and we may be able to detect them if they are ultimately accreted onto a white dwarf. While we see from Figures 1 and 2 that no known parent bodies are as refractory-rich as CAIs, perhaps they are subtly masked because their contribution to the observed pollution is diluted. There are two possibilities. First, dispersed refractory-dominated asteroids may have collided with "normal" asteroids and the resulting parent body is only enhanced in refractories but not dominated by them. Second, perhaps the observed white dwarfs have accreted multiple asteroids. Because only a minority of the parent bodies might have compositions dominated by refractories, then we would only detect an enhancement of refractories but not complete domination.

Before discussing these possibilities, we consider the entire observed ensemble of polluted white dwarfs. In both Figures 1 and 2, we see that there are Ca-deficient as well as Ca-enhanced objects. If the accreted parent bodies were blends of refractory-enhanced planetesimals with "normal" objects, there would not be any Ca-deficient asteroids. These data therefore favor models where, on average, calcium abundances are determined by processes in which asteroids differentiate, melt and collide. In such scenarios, refractory elements can

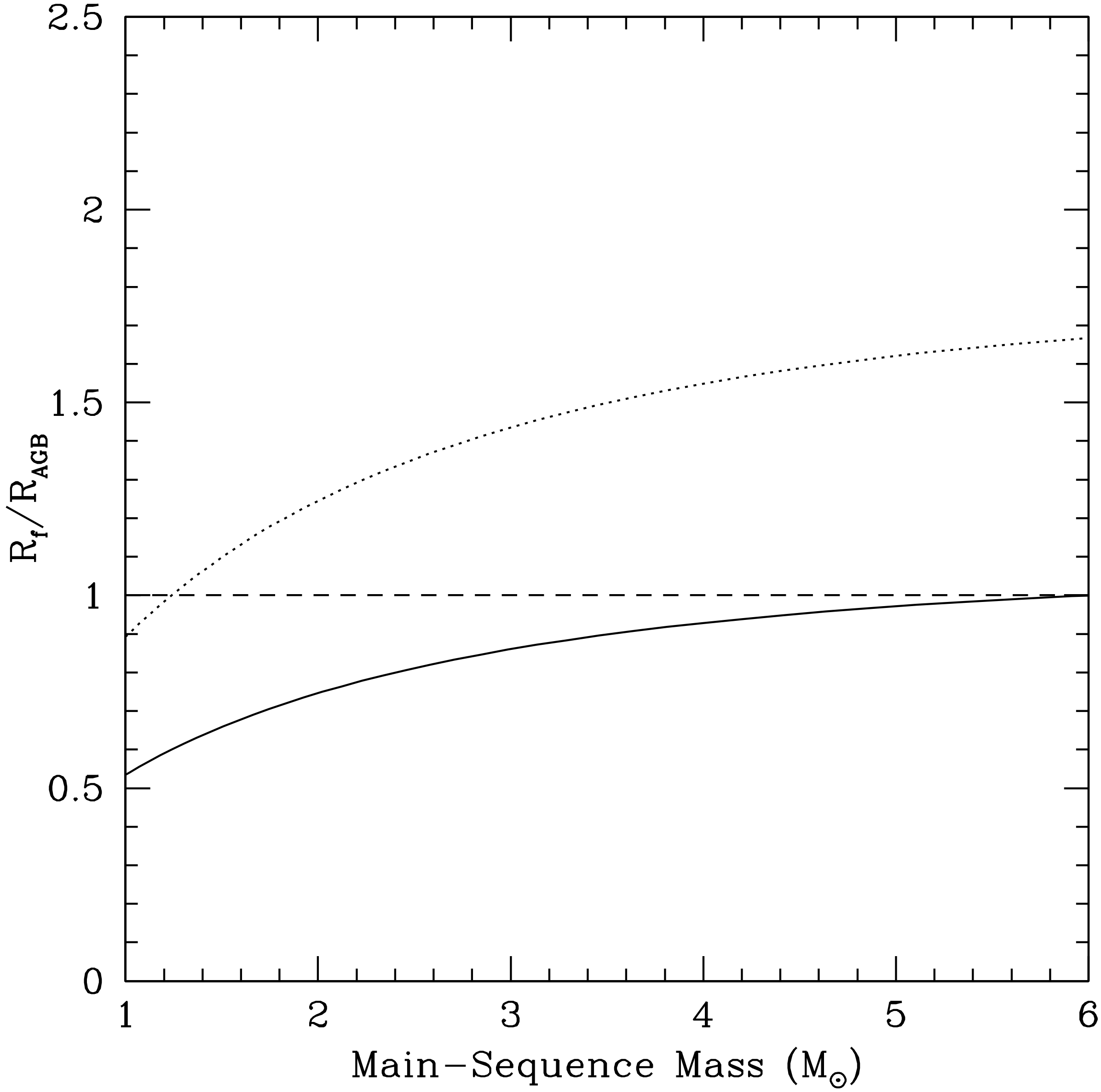

Fig. 3.— Display of R_f/R_{AGB} from Equation (14). The solid line shows the results the fiducial values of the opacity and viscosity. The dotted line shows the results if the opacity is increased by a factor of 10 or the viscosity parameter, α is decreased by a factor of 10. The horizontal dashed line defines the initial orbital location beyond which refractory-dominated planetesimals may survive into the star's white dwarf phase. At least in the fiducial case, exceptionally refractory planetesimals are not expected to survive the star's AGB evolution.

be exchanged among the planetesimal population, but there is no net enhancement. In contrast, if blending of refractory-dominated planetesimals into "normal" asteroids prevailed, then we would never detect objects which are Ca-deficient. Nevertheless, although there is no evidence from the ensemble of examined extrasolar asteroidal material for the formation of refractory-dominated planetesimals, there may be individual instances where this occurs and below we discuss this possibility.

4.1. Accretion of Compositionally-blended Parent Bodies?

To assess the possibility that there may be particular parent bodies which are composed of a blend of a refractory-dominated planetesimal with a "normal" object, we consider on a case-by-case basis those white dwarfs where the external pollution is comprehensively measured. Currently, as listed in Table 1, there are seven polluted dwarfs where at least seven elements heavier than helium, including all four major elements in bulk Earth - O, Mg, Si and Fe, have been detected and the results published. Equipped with these data, we can make a well-constrained estimate of the mass fractions carried in different elements, including the refractory elements measured in each star as listed in Table 1.

While the evolutionary history of each individual object is unknown, a parent body can be considered a candidate for a blend if every detected refractory element has a mass fraction significantly larger than its corresponding fraction in bulk Earth. Because typical uncertainties in abundance determinations are near 0.2 dex and because there is about 0.1 dex dispersion in the relative elemental abundances among main-sequence stars near the Sun, enhancements of an element's mass fraction by less than a factor of two are not clearly well-established. Furthermore, if the accreted parent body is a blend of a refractory-dominated planetesimal with an ambient object, then every refractory is expected to be enhanced.

- GD 40: In this star's pollution, the mass fractions of Ca and Ti are enhanced over bulk Earth's value. However, according to Jura et al. (2012a), the mass fraction of Al in this star's pollution is 0.013; slightly less than the value of 0.015 for bulk Earth (Allegre et al. 2001). There is no evidence for a blend.
- WD J0738+1835: According to Dufour et al. (2012) the mass fractions of Al, Ca, Ti and Sc are all below Earth's values. There is no evidence for a blend.
- PG 0843+516: Al is only 0.005 of the mass fraction of the accreted material (Gaensicke et al. 2012); less than bulk Earth's value of 0.015. There is no evidence for a blend.
- WD 1226+110: According to Gaensicke et al. (2012), while elevated, the mass fractions

of Al and Ca are less than a factor of two greater than bulk Earth's. Consequently, there is at best weak evidence for blending.

- WD 1929+012: According to Gaensicke et al. (2012), the mass fraction of Al is 0.002, much lower than bulk Earth's value. There is no evidence for a blend.

- G241-6: According to Jura et al. (2012a), the mass fraction of Al is less than 0.007. Consequently, there is no evidence for a blend.

- HS 2253+8023: Ti has essentially a solar mass fraction in the measured pollution of this star. Consequently, there is no evidence for a blend.

At least in this small sample of seven well-studied externally polluted white dwarfs, there is at best weak evidence that one parent body is a blend of a refractory-dominated planetesimal with an ambient asteroid.

Table 1 – Summary Evaluation of Possible Blending With a Refractory-Dominated Planetesimal

Star	T_{eff}	Dom.	No.	Refrac.	Dust	Blend	Ref.
GD 40	15,300	He	13	Al, Ca, Ti	Y	N	(a,b)
WD J0738+1835	13,950	He	14	Al, Ca, Ti, Sc	Y	N	(c)
PG 0843+516	23,100	H	10	Al	Y	N	(d,e)
WD 1226+110	20,900	H	7	Al, Ca	Y	?	(d)
WD 1929+012	21,200	H	12	Al, Ca	Y	N	(d,f,g)
G241-6	15,300	He	12	Ca, Ti	N	N	(b,h)
HS 2253+8023	14,400	He	9	Ca, Ti	N	N	(h)

The column headings are defined as follows. "Dom." reports the dominant light element in the atmosphere. "No." is the number of elements heavier than helium that are detected."Refrac" lists the detected refractory elements. "Dust" lists whether there is an infrared excess ('Y" = Yes and "N" = No), "Blend" gives our estimate of the likelihood for evidence that a refractory-dominated asteroid was blended into the parent body. "Ref" lists references. (a) Klein et al. (2010); (b) Jura et al. (2012a); (c) Dufour et al. (2012); (d) Gaensicke et al. (2012); (e) Xu & Jura (2012); (f) Vennes et al. (2011); (g) Melis et al. (2011); (h) Klein et al. (2011)

4.2. Single or Multiple Accretion Events?

Jura (2008) discussed whether we might be witnessing single or multiple accretion events

onto a polluted white dwarf. In this analysis, stars with dust disks are exhibiting the tidal disruption of one large parent body. That is, we would expect different asteroids to have slightly different orbital inclinations and once their solid material is tidally-disrupted, the mutual collision speeds in the Roche zone between the two sets of dust grains would be so great that the grains would be vaporized. Also, if extrasolar asteroids are at all like the solar system's, the bulk of the parent body mass is contained in a relatively few objects. It is therefore plausible that the accretion of large amounts of mass is from single objects. In fact, it is observed that the white dwarfs with the greatest amounts of pollution are likely to have a dust disk (Kilic et al. 2006; Farihi et al. 2012b).

In Figures 1 and 2, we distinguish between stars with dust disks and those without. We see no evidence that the stars with dust disks – objects likely polluted by a single large parent body – have a composition on average any different from those perhaps polluted by multiple asteroids. Therefore, these data do not provide any support for scenarios describing a long-term survival and subsequent accretion of intact refractory-dominated planetesimals.

5. PERSPECTIVE

Previous work has shown that extrasolar planetesimals at least qualitatively resemble rocky planets in the inner solar system because (i) they are largely composed of O, Mg, Si and Fe; (ii) C is usually deficient by at least an order of magnitude and (iii) H_2O usually is less than 1% of the bulk composition. These results where volatiles are always deficient can be understood as a result of a condensation sequence in the protoplanetary nebula (Lee et al. 2010; Lodders 2003). In contrast to the behavior of volatiles which are never seen to be enhanced, as shown in Figures 1 and 2, refractory elements such as calcium can be either deficient or enhanced. Therefore, as an ensemble, extrasolar planetesimals are more than a simple blend of refractory-dominated planetesimals with "normal" asteroids.

Further data will be most helpful. By measuring a large suite of elements in the composition of the parent body, detailed comparison with models becomes possible. A scenario of compositional reciprocity where one asteroid's loss is another's gain may explain much of the data for refractory elements in the entire ensemble of extrasolar planetesimals.

6. CONCLUSIONS

We have compiled from the literature measured values of $n(\mathrm{Ca})/n(\mathrm{Mg})$ and $n(\mathrm{Ca})/n(\mathrm{Fe})$ for externally-polluted white dwarfs; none of the accreted parent bodies are composed pri-

marily of refractory material. We argue on the basis of a toy model for protoplanetary nebula that unless dispersed from their original orbital location, refractory-dominated planetesimals likely would be destroyed during the star's AGB evolution. As yet, there is at best weak evidence to support the hypothesis that a refractory-dominated planetesimal was scattered from its zone of formation and then blended into material accreted onto an externally-polluted white dwarf.

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